JULY 1961

REPORT ESL-R-115
M.I.T. PROJECT DSR 7848
Contract AF-33(616)-5489
Task 50688

AN EXPERIMENTAL INVESTIGATION *of* NOISE *in* TUNNEL DIODES

Carl N. Berglund

...Systems Laboratory

Radar Research Group

...CHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE 39, MASSACHUSETTS

...ment of Electrical Engineering

NOTICE

The Servomechanisms Research Laboratory of the Electrical Engineering Department, Massachusetts Institute of Technology, announces a change in its name to ELECTRONIC SYSTEMS LABORATORY. This new name reflects the importance of systems concepts in modern engineering, and the interrelationship in many complex systems among control technology, data processing, and electronic measuring devices and systems. The Electronic Systems Laboratory is currently engaged in research in computer technology and applications, control technology, electronic measuring systems, and related devices and components.

****

NOTICE

July 1961 Report ESL-R-115 Copy 23

AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES

by

Carl N. Berglund

The research reported in this document was made possible through the support extended the Massachusetts Institute of Technology, Electronic Systems Laboratory, by the United States Air Force (Navigation and Guidance Laboratory, Aeronautical Systems Division) under Contract AF-33(616)-5489, Task 50688, M. I. T. Project DSR 7848. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency.

Radar Research Group
Electronic Systems Laboratory
Department of Electrical Engineering
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

NOTICES

Requests for additional copies by Agencies of the Department of Defense, their contractors, and other Government agencies should be directed to the:

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

Department of Defense contractors must be established for ASTIA services or have their "need-to-know" certified by the cognizant military agency of their project or contract.

ABSTRACT

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

ACKNOWLEDGMENT

This report is based on a thesis submitted by Carl N. Berglund in September 1961 in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering at the Massachusetts Institute of Technology.

The author wishes to express his appreciation to the staff of the Electronic Systems Laboratory, particularly Mr. Godfrey T. Coate for his supervision of this work and for his valuable suggestions and criticisms.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

CHAPTER I

INTRODUCTION AND SUMMARY OF RESULTS

A. OBJECT OF THE STUDY

In order to determine whether the tunnel diode will be useful in low-noise preamplifiers, frequency converters and mixers, more complete information than is available in the literature is required on the noise sources present in the device.

The object of the present work is to measure the intensity of the equivalent shunt noise-current generator for a number of commercially available tunnel diodes over a wide range of bias, frequency, and temperature, and to interpret the results in terms of noise sources present in the diodes.

B. MEASURED NOISE IN SOME TUNNEL DIODES

Measurements were made on four tunnel diodes: one Hoffman silicon tunnel diode, Type 1N2929, of 1-ma peak current, and three General Electric germanium tunnel diodes, Types 1N2939, 1N2969, and 1N2941, of 1-, 2.2-, and 4.7-ma peak currents, respectively. These four were chosen in an effort to obtain a reasonable sample of commercially available tunnel diodes.

The measurements were made at three temperatures, 203 K, 290 K, and 373 K, and covered a frequency range from 1 kc to 500 kc. Noise was also measured at 30 Mc at room temperature. The bias range of interest extended from zero voltage to voltages slightly beyond the valley voltage.

The more important results of the study are as follows.

1. <u>Frequency-Dependent Noise</u>

At low frequencies, considerable $1/f$ noise was found to be present in all four diodes. Figure 1a shows the d-c characteristic and Figs. 1b and 1c illustrate the magnitude of the noise measured in the 2.2-ma

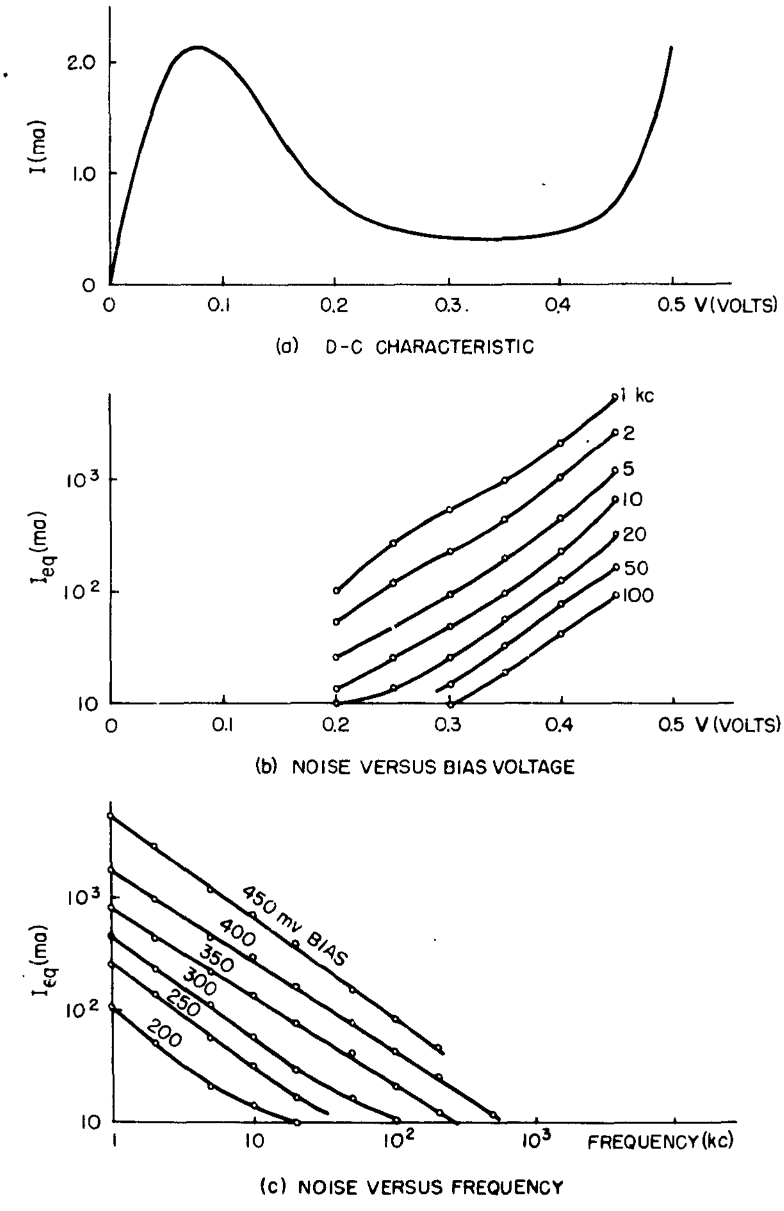

Fig. 1 Characteristics at 290 K of 2.2-ma Ge Tunnel Diode Type 1N2969 (No. 1)

germanium sample at room temperature, 290 K. The equivalent shot-noise current I_{eq} represents the direct current in an emission-saturated diode generating a shot noise current equal to the observed noise current, where I_{eq} is defined by the equation

$$\overline{i_d^2} = 2\, q\, I_{eq}\, \Delta f \tag{1}$$

In eq. 1, $\overline{i_d^2}$ is the mean-square noise-current generator in shunt with the tunnel diode at the frequency, temperature, and bias of the measurement, q is the electronic charge, and Δf is the bandwidth of the noise measured.

From Fig. 1b it can be seen that low-frequency noise in tunnel diodes increases rapidly with increasing bias voltages, and Fig. 1c indicates that the noise varies roughly in proportion to $1/f$. At the higher bias voltages, the noise may be so large that a frequency dependent component may be present that is greater than the normal shot-noise component to frequencies as high as 50 Mc.

Figure 2 shows 1-kc noise in all four diodes, and also in a second sample of the 2.2-ma diode Type 1N2969, as a function of forward current, and suggests that no general statements can be made about the magnitude of low-frequency noise to be expected from a diode of given peak-current rating. In addition, the noise does not vary directly as the square of the forward current, indicating that more than one source is responsible for the observed noise.

The approximate $1/f$ frequency variation indicated in Fig. 1c is not characteristic of all the diodes. However, at a particular bias voltage, the low-frequency noise in all samples was found to vary nearly inversely as the frequency to some power x. The value of x varies over a considerable range with bias voltage and temperature. Values as low as 0.46 and as high as 1.2 were noted.

In the work of Yajima and Esaki,[1] it was suggested that two low-frequency noise-current generators were present in the tunnel diode, one proportional to the square of the normal diode current component, and one

---

1 Superscripts refer to numbered items in the Bibliography.

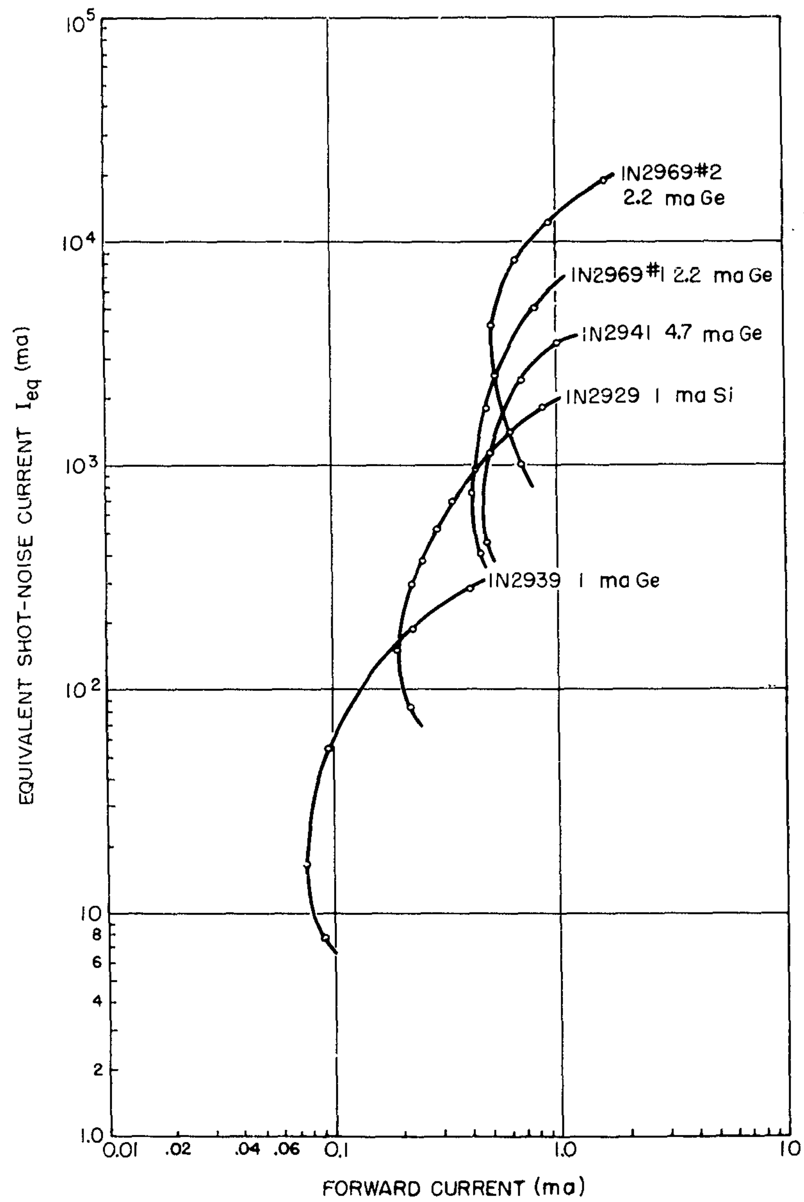

Fig. 2 1-kc Noise vs. Forward Current in Five Tunnel-Diode Samples at 290 K proportional to the square of the "excess" current component. The results of the present study suggest that this statement may be an oversimplification. The variation of the factor x as described above, and the variation of the 1/f noise with bias in the excess-current region indicate that two or more separate components of the excess current, as well as the diode current component, contribute to the observed noise. This observation in turn suggests that the excess current itself may be caused by more than one physical phenomen

2. Frequency-Independent Noise

At high frequencies, the 1/f noise becomes negligible and the predominant noise-current source in tunnel diodes is the shot effect. Measurements by Tiemann[2] have shown that at high frequencies and in the negative-resistance region tunnel diodes produce full shot noise; that is, I_{eq} is equal to the direct current at the bias point. It is supposed that this result can be extended to other bias regions if the negative Zener current I_Z is separated from the positive Esaki, excess, and diode current components, I_E, I_{ex}, and I_d respectively. Thus, if

$$I_{dc} = I_E + I_{ex} + I_d - I_Z \tag{2}$$

is the diode direct current, it is supposed that

$$I_{eq} = I_E + I_{ex} + I_d + I_Z \tag{3}$$

Measurements made at 30 Mc and 290 K indicate that, for all four tunnel-diode samples, Eq. 3 is an excellent approximation. An example of the agreement obtained is shown by data for the 1-ma germanium diode, Type 1N2939, plotted in Fig. 3. The small circles represent experimental values of I_{eq} and the solid line is a plot of Eq. 3 obtained from the direct current values and values of I_Z calculated by a method given by Pucel.[3*] The dashed line representing I_{dc} is added for comparison.

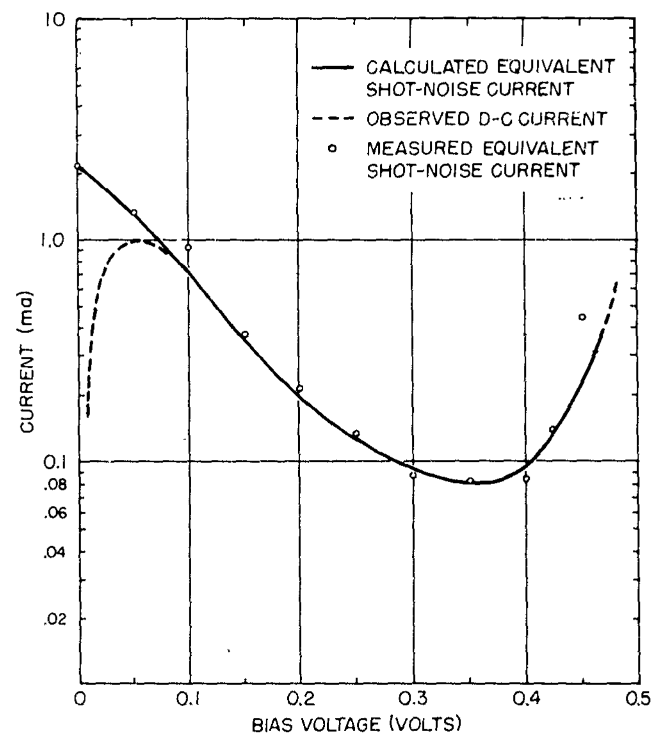

Fig. 3 Comparison of Calculated and Measured Equivalent Shot-Noise Current at 30 Mc and 290 K for 1-ma Ge Tunnel Diode Type 1N2939

---

* A description of the method is given in Chapter III.

CHAPTER II

MEASUREMENT PROCEDURE

A. LOW-FREQUENCY NOISE MEASUREMENTS

The equivalent noise-current generator in shunt with a tunnel diode can be determined indirectly by connecting the diode as a low-gain amplifier and measuring its noise figure. The circuit diagram for noise measurements between 1 kc and 500 kc is shown in Fig. 4.

The experimental procedure is as follows: With the tunnel diode connected as shown, and the conductance G set at some convenient value G_1 which prevents the circuit from oscillating, note the voltage V_1 indicated on the true-rms voltmeter. Connect the signal generator to the circuit,

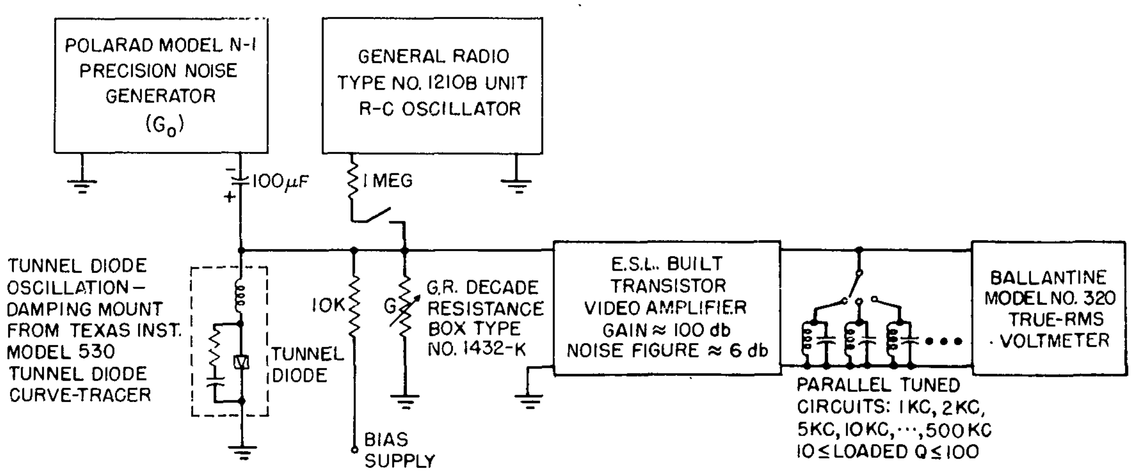

Fig. 4 Circuit for Low-Frequency Noise Measurements

and set its output to some convenient value well above the noise. Remove the tunnel diode and adjust the conductance G to some value G_2 for which the voltmeter reading is the same as it was before. This procedure assures that the impedance seen by the amplifier at its input is the same as it was for the first measurement. With the signal generator disconnected, note the voltage V_2 of the voltmeter and measure the noise figure, F_2, of the circuit. The internal conductance of the noise generator is G_0 for both measurements.

From the two measurements, the equivalent noise generator $\overline{i_d^2}$ in parallel with the tunnel diode in a narrow bandwidth Δf at the frequency, temperature, and bias of the measurement can be calculated. Figures 5 and 6 are the equivalent circuits of the amplifier input for the first and second measurements respectively. In the figures, G_d is the small-signal conductance

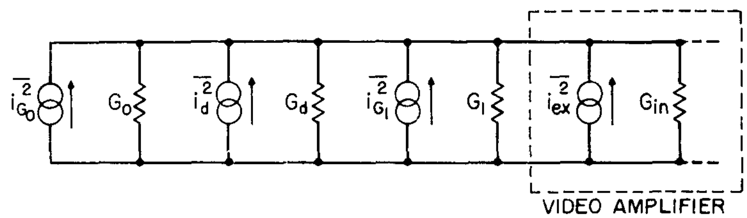

Fig. 5 Noise Equivalent Circuit at Input of Video Amplifier with Tunnel Diode Connected

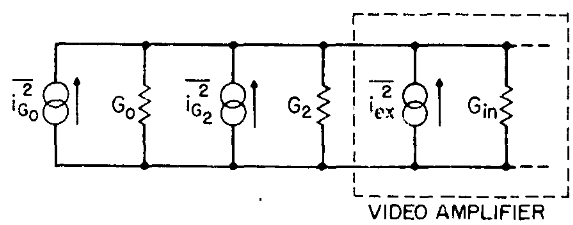

Fig. 6 Noise Equivalent Circuit at Input of Video Amplifier with Tunnel Diode Removed

of the tunnel diode at the bias voltage of the measurement, G_{in} is the input conductance of the amplifier, and $\overline{i_{G_0}^2}$, $\overline{i_{G_1}^2}$, and $\overline{i_{G_2}^2}$ are the mean-square thermal-noise currents associated with the conductances G_0, G_1, and G_2 respectively. Thus

$$\overline{i_{G_0}^2} = 4\,kT\,\Delta f\,G_0 \tag{4}$$

$$\overline{i_{G_1}^2} = 4\,kT\,\Delta f\,G_1 \tag{5}$$

$$\overline{i^2_{G_2}} = 4\ kT\ \Delta f\ G_2 \tag{6}$$

where k is Boltzmann's constant, and T is the absolute temperature of the conductances (290 K for all measurements). The amplifier noise is represented by an equivalent noise-current generator at its input terminals of mean-square value $\overline{i^2_{ex}}$.

For the first measurement,

$$V_1^2 = (\overline{i^2_d} + \overline{i^2_{G_0}} + \overline{i^2_{G_1}} + \overline{i^2_{ex}})\ C_1 \tag{7}$$

where C_1 is some constant dependent on the amplifier gain and the total admittance at the amplifier's input. For the second measurement

$$V_2^2 = (\overline{i^2_{G_2}} + \overline{i^2_{G_0}} + \overline{i^2_{ex}})\ C_1 \tag{8}$$

$$F_2 = \frac{\overline{i^2_{G_2}} + \overline{i^2_{G_0}} + \overline{i^2_{ex}}}{\overline{i^2_{G_0}}} \tag{9}$$

and the values of C_1 and $\overline{i^2_{ex}}$ are unaltered because the method of setting G_2 assures that the total input admittance is not changed. From Eqs. 7 and 8,

$$\overline{i^2_d} + \overline{i^2_{G_0}} + \overline{i^2_{G_1}} + \overline{i^2_{ex}} = \left(\frac{V_1}{V_2}\right)^2 \left(\overline{i^2_{G_2}} + \overline{i^2_{G_0}} + \overline{i^2_{ex}}\right) \tag{10}$$

Substituting Eqs. 4, 5, 6, and 9 into Eq. 10 yields

$$\overline{i^2_d} = 4\ kT\ \Delta f\ G_0 \left\{\left[\left(\frac{V_1}{V_2}\right)^2 - 1\right] F_2 + \frac{G_2}{G_0} - \frac{G_1}{G_0}\right\} \tag{11}$$

If I_{eq} is defined as the equivalent shot-noise current of the tunnel diode given by

$$\overline{i_d^2} = 2\, q\, I_{eq}\, \Delta f \qquad (12)$$

Equation 11 becomes

$$I_{eq} = \frac{2\, kT\, G_0}{q} \left\{ \left[\left(\frac{V_1}{V_2} \right)^2 - 1 \right] F_2 + \frac{G_2}{G_0} - \frac{G_1}{G_0} \right\}$$

$$\approx 50\, G_0 \left\{ \left[\left(\frac{V_1}{V_2} \right)^2 - 1 \right] F_2 + \frac{G_2}{G_0} - \frac{G_1}{G_0} \right\} \text{ ma} \qquad (13)$$

Equation 13 holds regardless of the tunnel-diode temperature.

Measurements were made at dry-ice temperature, 203 K, room temperature, 290 K, and 373 K. To maintain the diodes at dry-ice temperature, the samples and their mount were placed with some dry ice in a flask of alcohol. A temperature-controlled oven was used for noise measurements of the samples at 373 K.

The oscillation-damping mount used for the tunnel diodes was taken from a Texas Instruments Model 530 Tunnel Diode Curve Tracer. It consists of a series resistance and capacitance placed directly across the tunnel diode terminals. The value of the capacitance is such that even at the highest frequency of measurement, 500 kc, its impedance is high enough to make the effect of the mount on the noise measurements negligible.

B. HIGH-FREQUENCY NOISE MEASUREMENTS

The equivalent noise-current generator in shunt with the tunnel diodes was measured at 30 Mc by a similar method to that used at low frequencies. The circuit diagram is shown in Fig. 7.

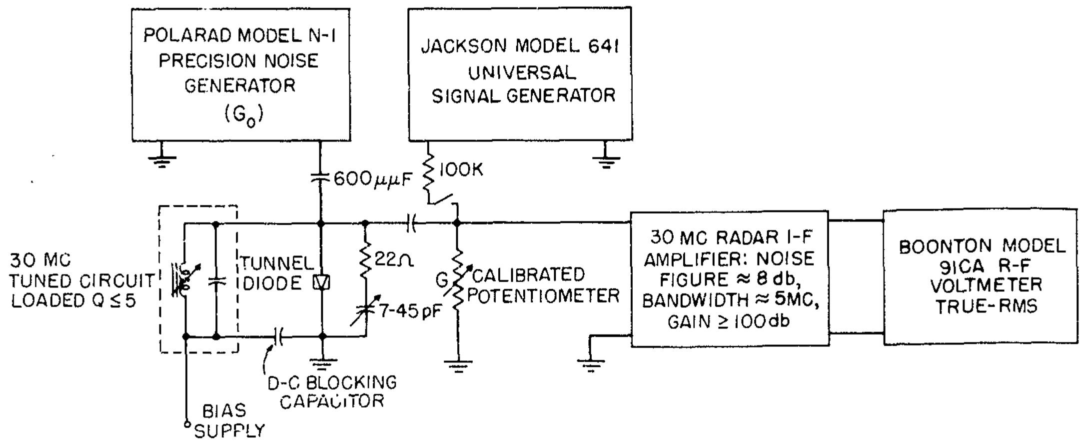

Fig. 7 Circuit for 30-Mc Noise Measurements

The procedure of measurement at 30 Mc is the same as that at low frequencies, except that the tuned circuit must be retuned before each measurement to correct for the effect of tunnel-diode capacitance. The equivalent shot-noise current is again given by Eq. 13.

Measurements were made only at room temperature because oscillation of the tunnel-diode circuit was caused by the long connecting cable required between the noise-measuring equipment and the temperature-controlling equipment. The oscillation-damping network shown in Fig. 7 consists of a series resistance of 22 ohms and a variable capacitor of 7 to 45 mmf placed directly across the diode terminals. The method of calculating the values required was that of Davidsohn et al.[4] The value of capacitance must be such that the noise contribution to the circuit of the 22-ohm resistor is negligible with respect to that of the diode at 30 Mc. For this reason, a much smaller value of capacitance than that used for the low-frequency measurements was required. This resulted in insufficient damping when long connecting cables were used, and the diodes oscillated.

C. DISCUSSION OF ERRORS

The method of noise measurement employed has the advantage of tending to reduce the effect of inaccuracies in some of the measuring equipment. Consider Eq. 13 rewritten in a slightly different manner.

$$I_{eq} = 50 \left[\left(\frac{V_1}{V_2} \right)^2 - 1 \right] F_2 G_0 + 50\, G_2 - 50\, G_1 \text{ ma.} \tag{14}$$

The accuracy of I_{eq} is to a large part determined by the accuracy of the factor $(V_1/V_2)^2 - 1$. The ratio V_1/V_2 may be more accurate than either V_1 or V_2 taken alone if some of the error in V_1 appears proportionally in V_2. For best accuracy, the ratio V_1/V_2 must be much greater than unity. But V_1/V_2 can be large only if the product G_0F_2 is small. Thus, an amplifier with as low a noise figure as possible and a value of G_0 as small as possible (consistent with low over-all noise figure) should be used.

The value of I_{eq} can also be determined by measuring the over-all system noise figure F_1 instead of V_1 in the first step of the measurement. The equivalent noise current I_{eq} is then given by

$$I_{eq} = 50\, G_0 \left[F_1 - F_2 + \frac{G_2}{G_0} - \frac{G_1}{G_0} \right] \text{ ma} \tag{15}$$

However, the many more operations associated with measuring F_1 and F_2 rather than V_1, V_2, and F_2 makes this method more time consuming. Also, the upper limit on F_1 of 20 db set by the noise generator restricts the range of I_{eq}, and the fact that the true-rms voltmeter is more accurately calibrated than the noise generator makes the error of the measurement associated with Eq. 14 smaller than that of the measurement associated with Eq. 15.

Any small stray reactance present in the circuit, if it is the same for the measurement of V_1 as for that of V_2, will appear chiefly in the value of C_1 in Eqs. 7 and 8. Thus, its effect on the accuracy of I_{eq} is minimized.

CHAPTER III

DISCUSSION OF RESULTS

A. TUNNEL-DIODE CURRENT MECHANISMS

Figure 8 shows a typical current-voltage characteristic of a tunnel diode. A knowledge of the carrier-transport phenomena that combine to form the observed characteristic is required if the experimental noise data are to be interpreted in terms of noise sources within the device.

In the large-forward-voltage range, the observed curve is due to electron and hole diffusion in the forward direction, and drift currents in the reverse direction. This component of current, I_d, can be determined by accurately measuring current and voltage in the tunnel diode at high forward voltage, and applying the usual diode current-voltage relation[1]

$$I_d = I_s \left[e^{qV/kT} - 1 \right] \tag{16}$$

where q is the electronic charge, k is Boltzmann's constant, T is the absolute temperature, I_s is a constant, and V is the barrier voltage. The voltage drop in the diode spreading resistance must be subtracted from the measured voltage to obtain V.

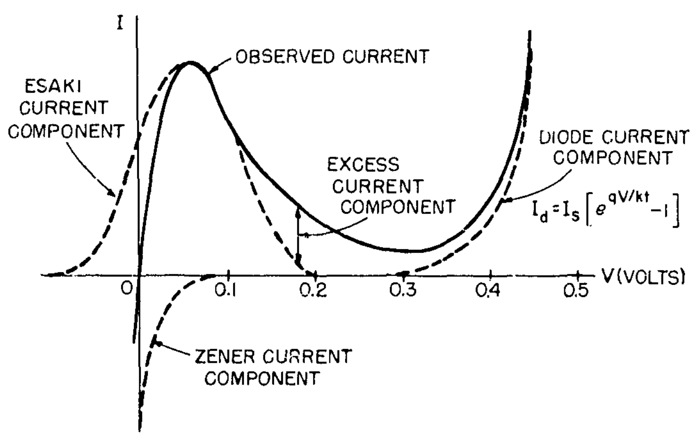

Fig. 8 Typical Tunnel-Diode V-I Characteristics

Large current in the reverse direction and a current peak in the forward direction can be attributed[1] to the forward-directed Esaki current I_E and the reverse-directed Zener current I_Z. The magnitudes of these two currents have not been accurately predicted by present theory. However, between zero voltage and the voltage at the peak current, the two components can be calculated from the observed d-c characteristic quite closely by using a method suggested by Pucel.[3] If I is the observed current, then the Esaki and Zener current components at some voltage V are given by

$$I_E = \frac{I}{1-e^{-qV/kT}} \tag{17}$$

$$I_Z = \frac{I}{e^{qV/kT}-1} \tag{18}$$

This method is not applicable at bias voltages above approximately the peak-point voltage because the current then contains components in addition to I_E and I_Z.

If a parabolic band structure is assumed for the tunnel diode, I_E and I_Z can be predicted, but a d-c characteristic obtained using these values does not agree with observed values of total current. The difference between the observed current and the algebraic sum of the calculated Esaki, Zener and diode current components has been called the excess current, I_{ex}, and is generally believed to be due to carrier tunneling to intermediate states followed by recombination. This excess-current component, along with the diode component, are thought to be almost entirely responsible for $1/f$ noise in the device.[1]

B. 1/f NOISE IN TUNNEL DIODES

In 1958, as a method of learning more about the excess-current region of the tunnel-diode current-voltage characteristic, an experimental study of excess noise in the device was made by Yajima and Esaki.[1] It was found that a $1/f$ noise spectrum existed which appeared to be proportional to the excess current.

Figures 9 through 18 show the noise observed in the tunnel diode samples at low frequencies. Figures 9 through 16 are plots of observed noise versus frequency and observed noise versus bias voltage for each of the Type 1N2929, 1N2939, 1N9241, and 1N2969 samples at temperatures of 203 K, 290 K, and 373 K. Figure 17 shows the variation of observed noise with frequency and bias voltage for a second sample of the Type 1N2969 2.2-ma tunnel diode at room temperature. Figure 18 shows the variation of observed 1-kc noise with forward current for each of the four samples at the three temperatures 203 K, 290 K, and 373 K. The d-c characteristics for the four samples at the three temperatures are given by Figs. 19, 20, 21, and 22.

Yajima[1] assumed that there are two $1/f$ noise-current generators present in tunnel diodes, one proportional to the square of the diode-current component and one proportional to the square of the excess-current component. On this assumption, the following approximate equation can be written

$$I_{eq} = \frac{K_1 I_d^2}{f} + \frac{K_2 I_{ex}^2}{f} \tag{19}$$

where K_1 and K_2 are constants, and f is the frequency of the noise.

An attempt to fit Eq. 19 to the measured data yields widely different values of K_1 and K_2 for the different diodes. In fact, variation of K_1 and K_2 is needed even from region to region of a single diode. However, it can be said in general that K_2 is much greater than K_1. The magnitude of the excess noise at any particular bias point was found to be nearly inversely proportional to its frequency to some power x. The value of x varied from 0.46 to 1.2, and was in general large at the higher bias voltages.

These observations seem to suggest that Eq. 19 is not correct. Instead, it seems reasonable to suppose that the excess current is made up of a number of components which produce excess noise inversely proportional to different powers of frequency and at different intensities. Since the

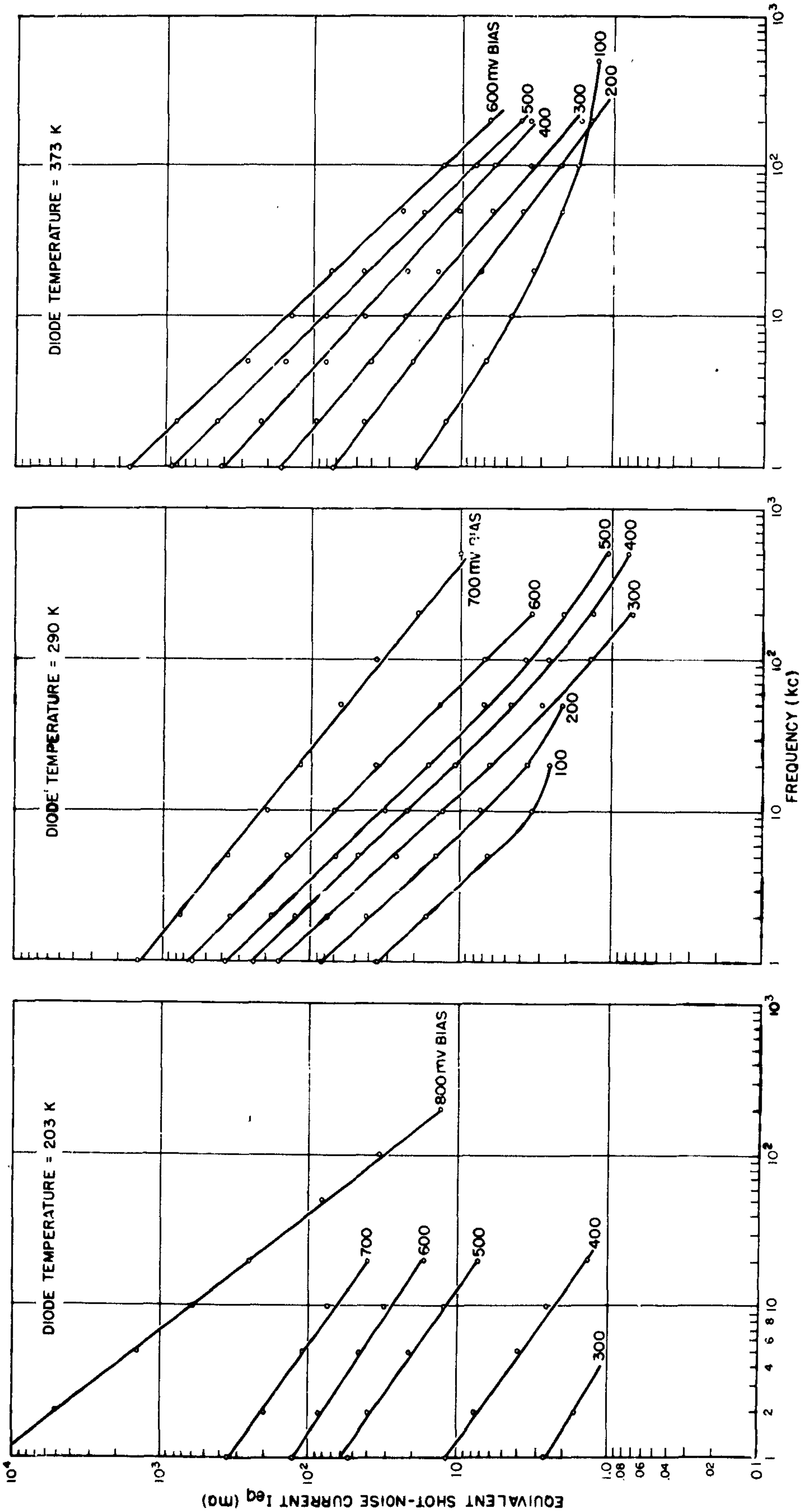

Fig. 9 Low-Frequency Noise vs. Frequency for 1-ma Si Tunnel Diode Type 1N2929

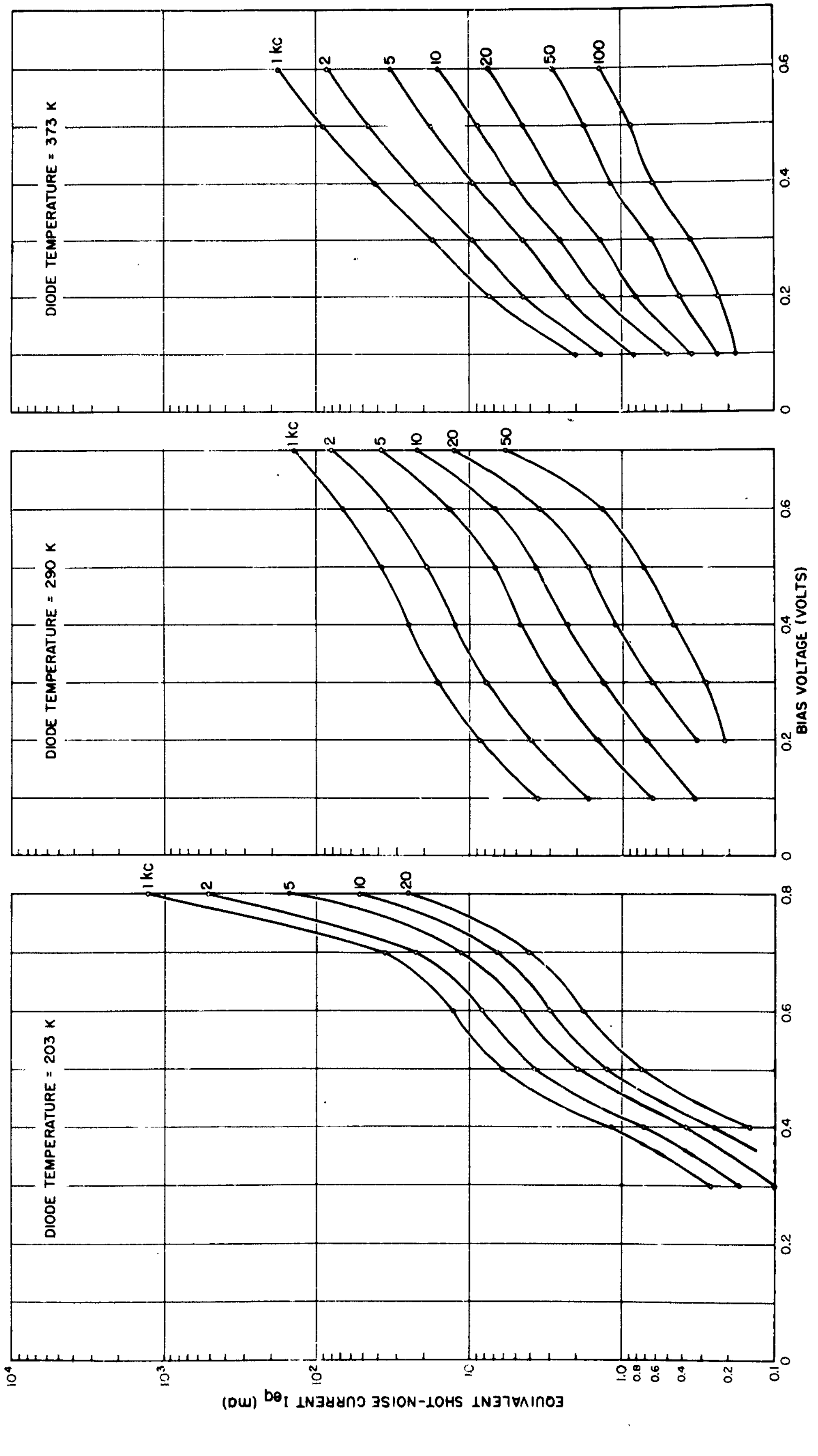

Fig. 10 Low-Frequency Noise vs. Bias Voltage for 1-ma Si Tunnel Diode Type 1N2929

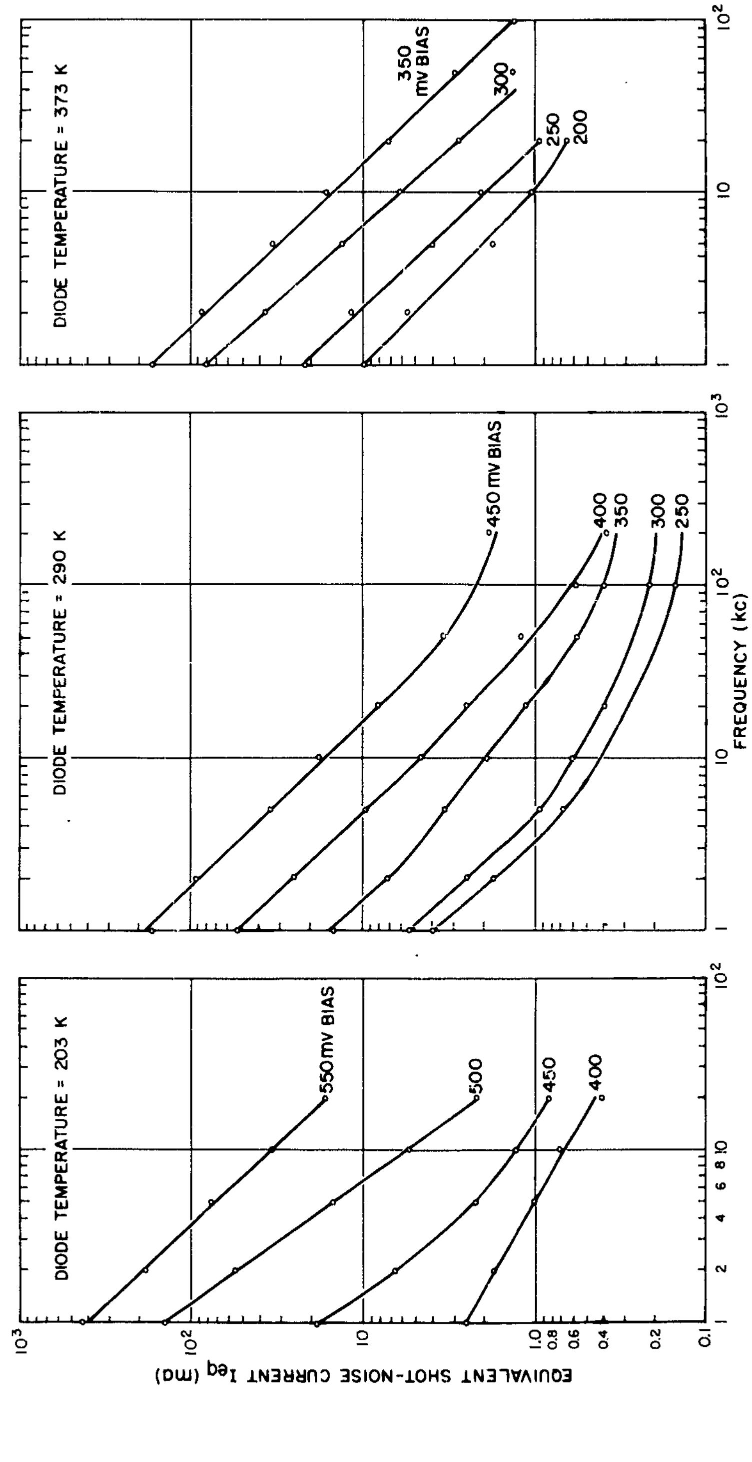

Fig. 11 Low-Frequency Noise vs. Frequency for 1-ma Ge Tunnel Diode Type 1N2939

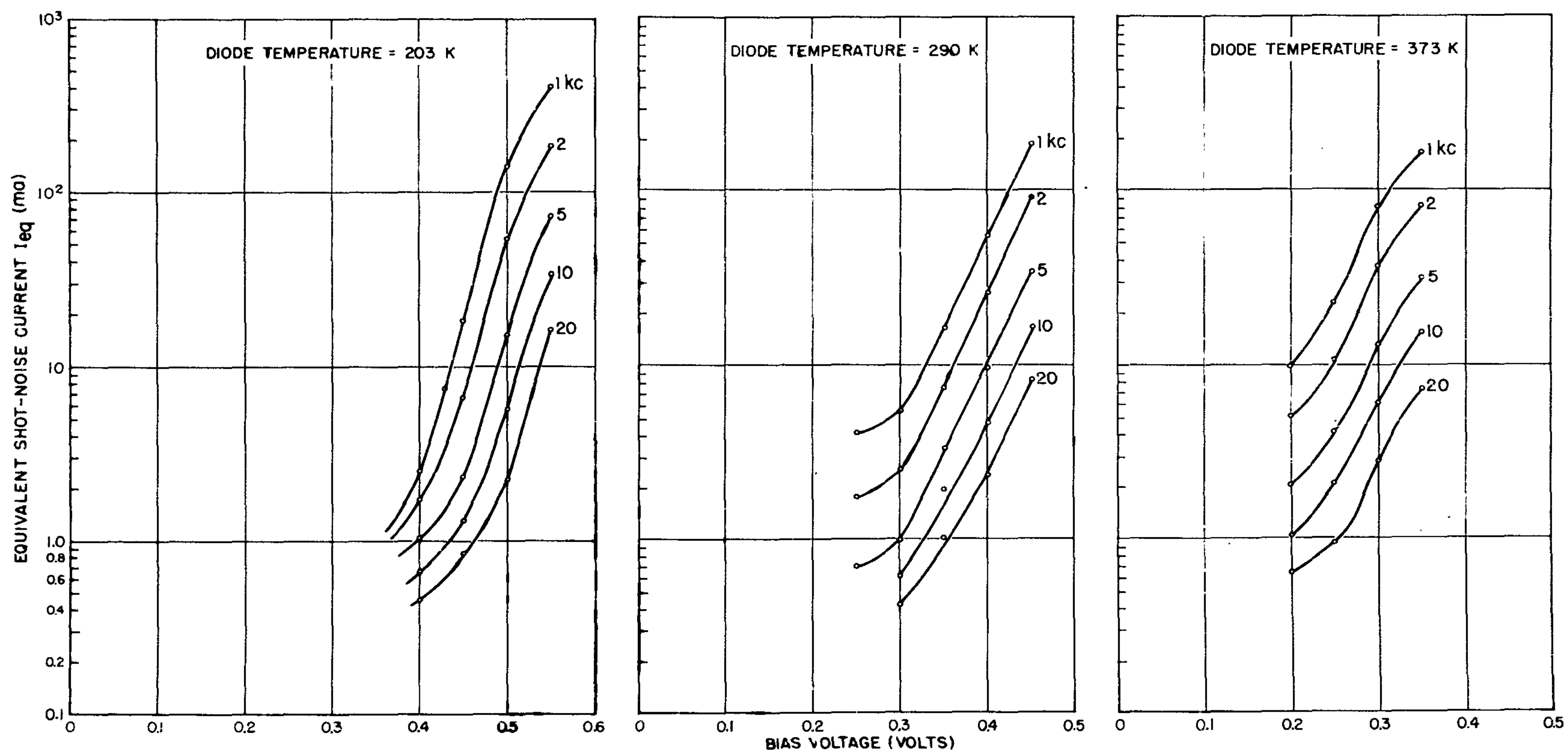

Fig. 12 Low-Frequency Noise vs. Bias Voltage for 1-ma Ge Tunnel Diode Type 1N2939

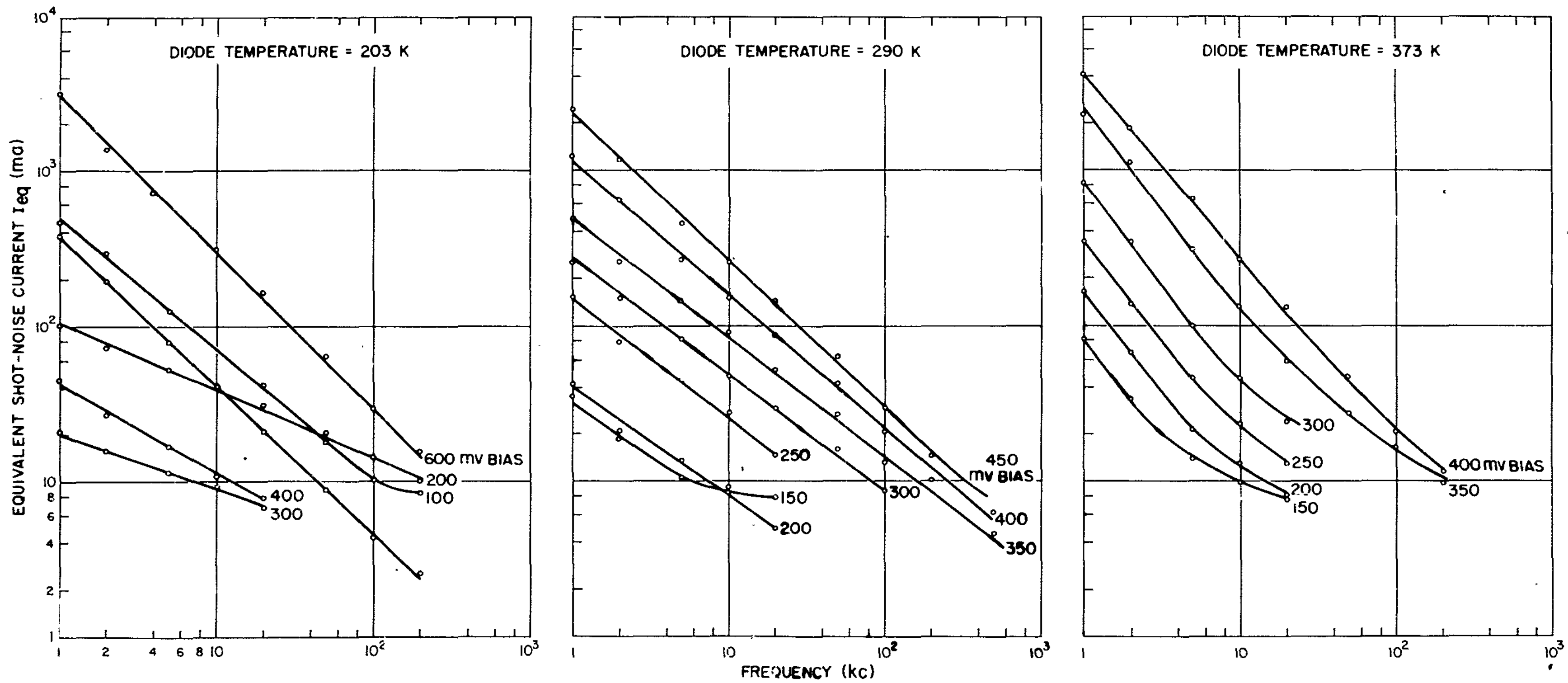

Fig. 13 Low-Frequency Noise vs. Frequency for 4.7-ma Ge Tunnel Diode Type 1N2941

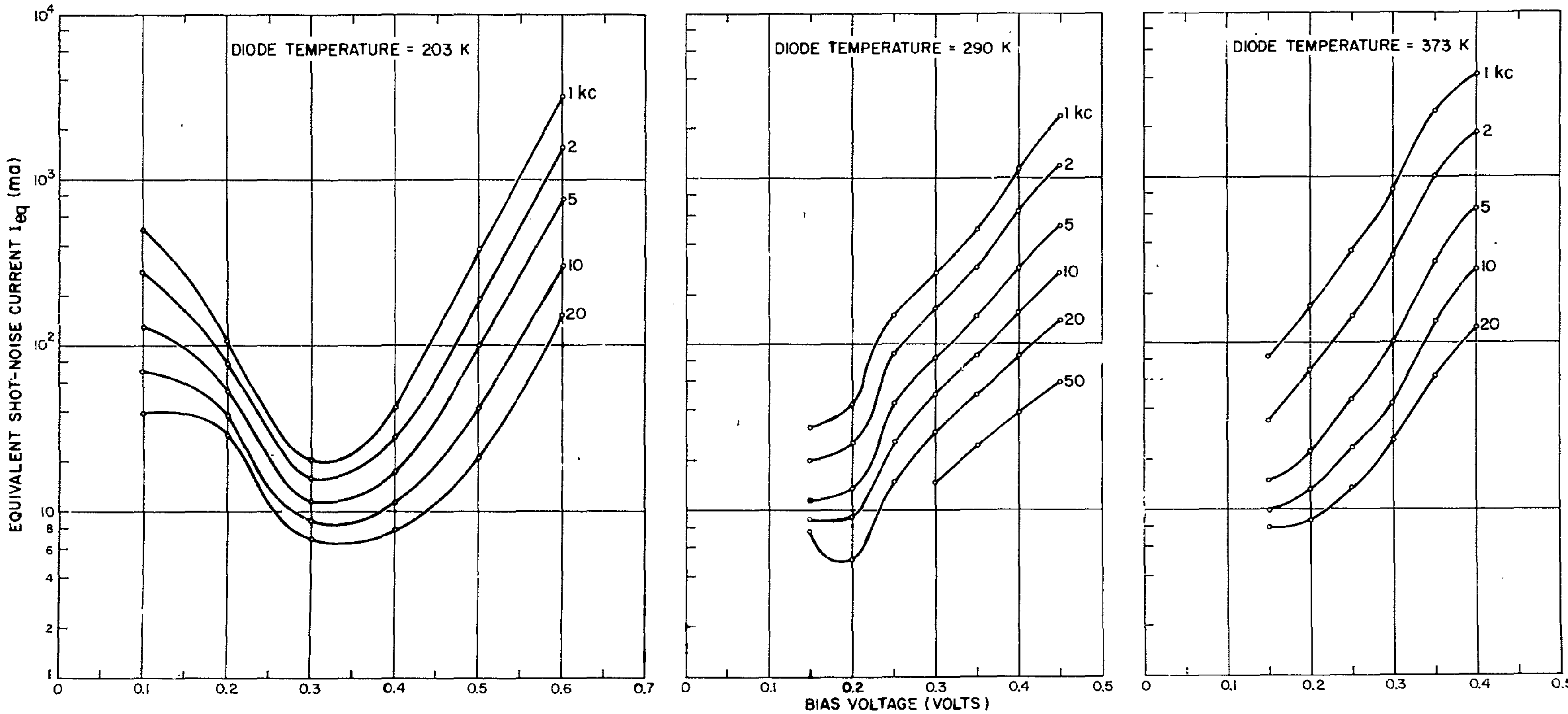

Fig. 14 Low-Frequency Noise vs. Bias Voltage for 4.7-ma Ge Tunnel Diode Type 1N2941

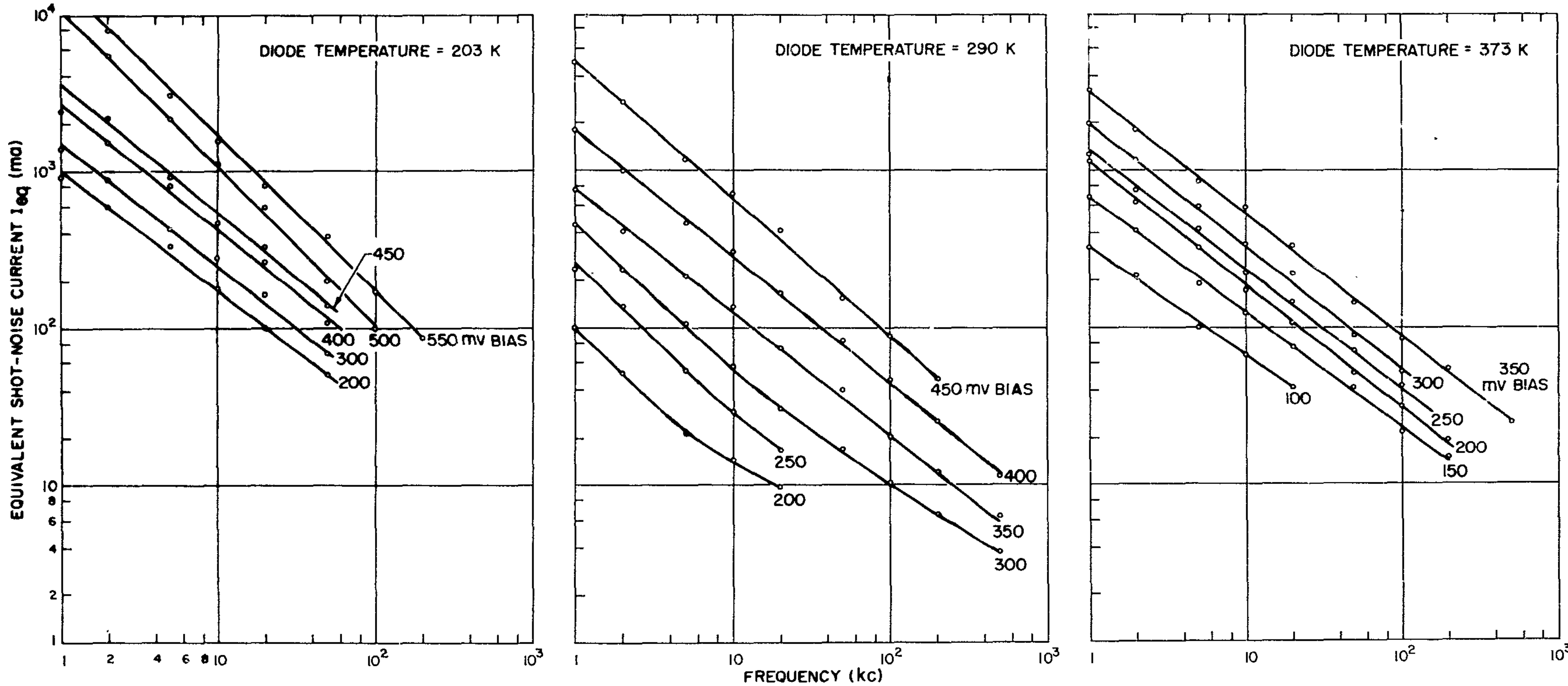

Fig. 15 Low-Frequency Noise vs. Frequency for 2.2-ma Ge Tunnel Diode Type 1N2969 (No. 1)

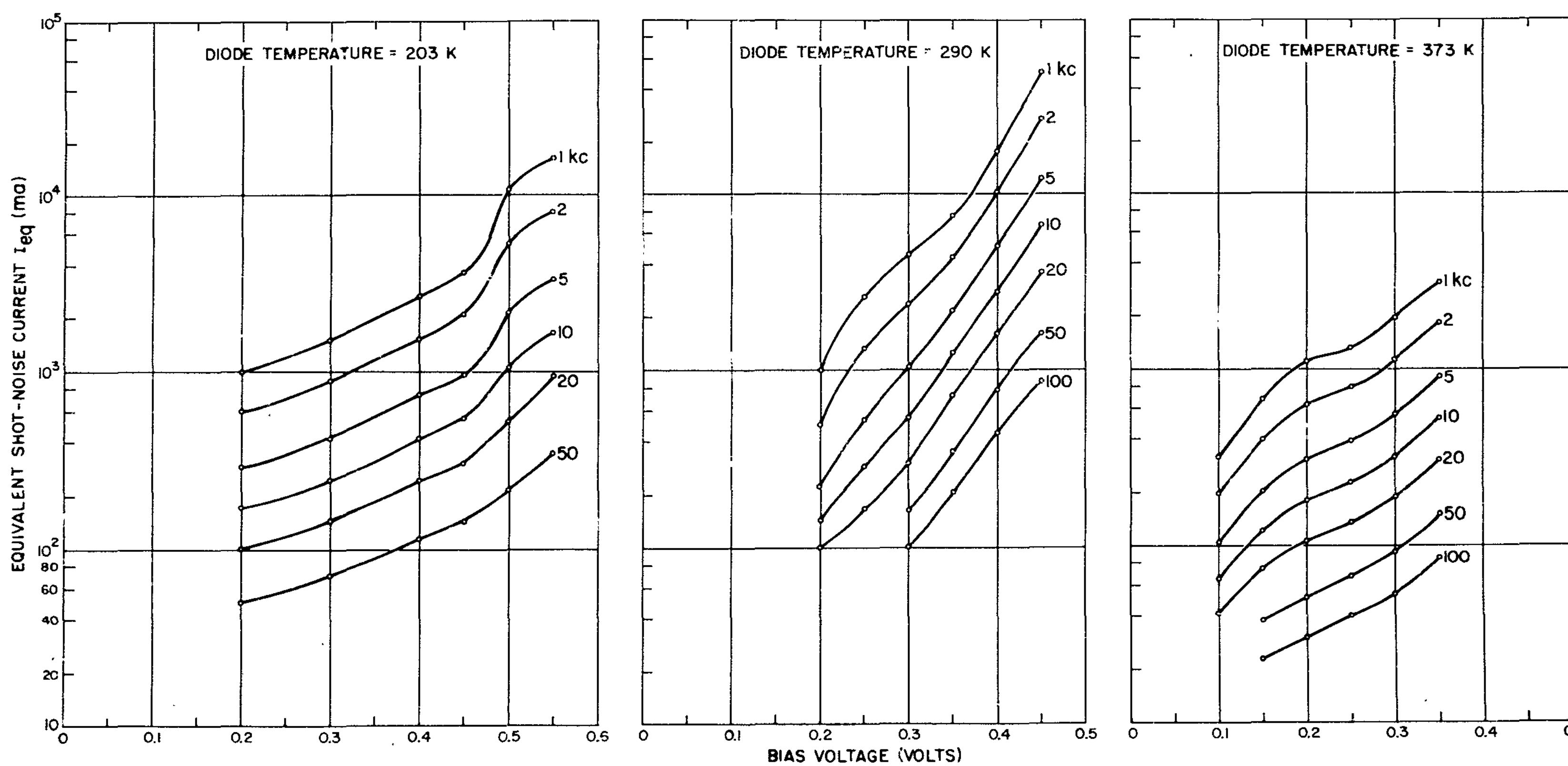

Fig. 16 Low-Frequency Noise vs. Bias Voltage for 2.2-ma Ge Tunnel Diode Type 1N2969 (No. 1)

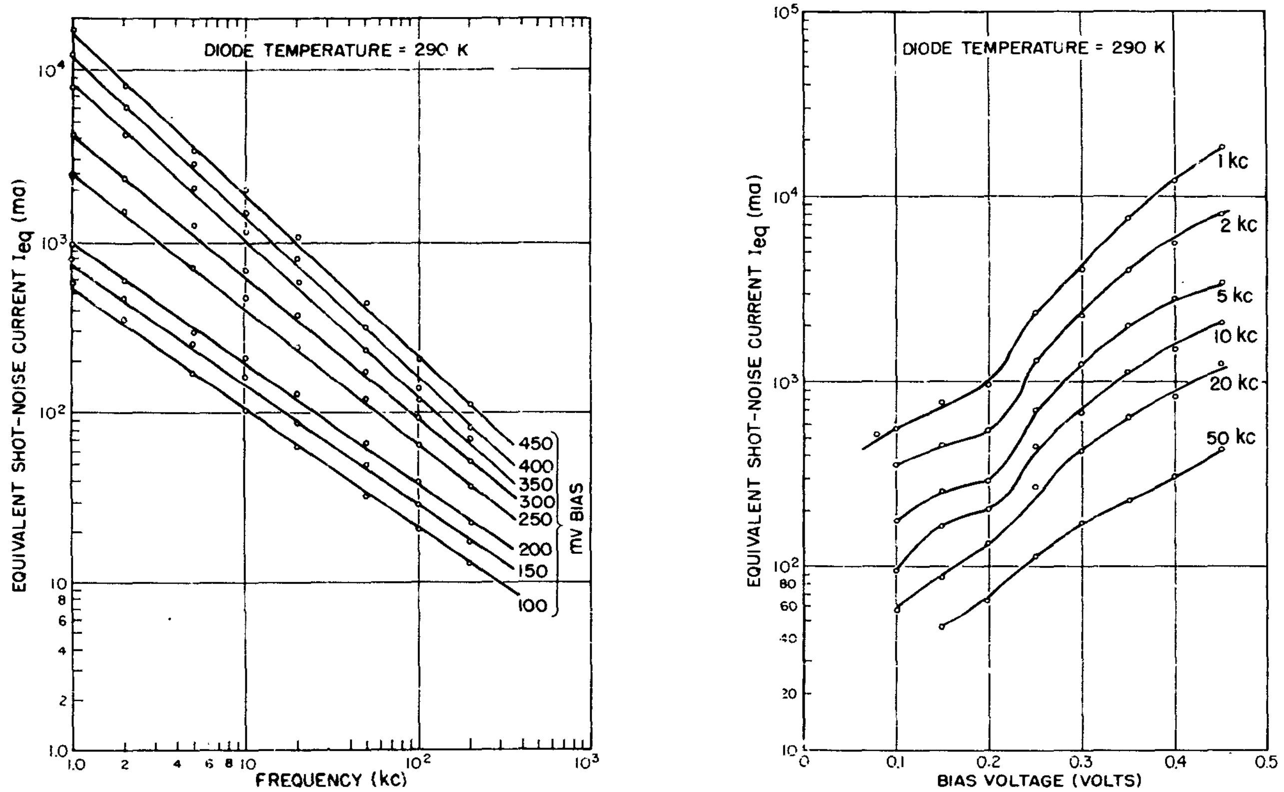

Fig. 17 Low-Frequency Noise at 290 K for 2.2-ma Ge Tunnel Diode Type 1N2969 (No. 2)

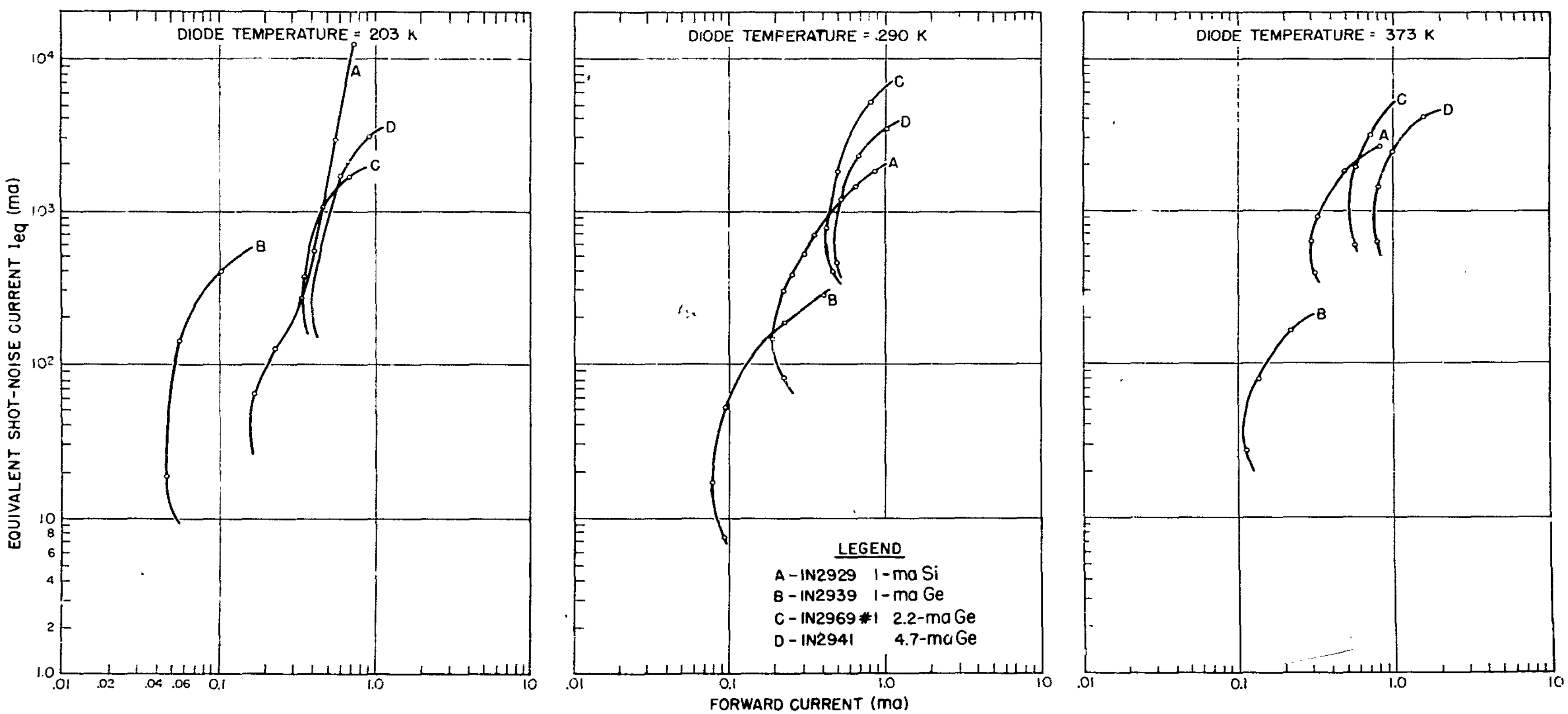

Fig. 18 1-kc Noise in Tunnel-Diode Samples vs. Forward Current

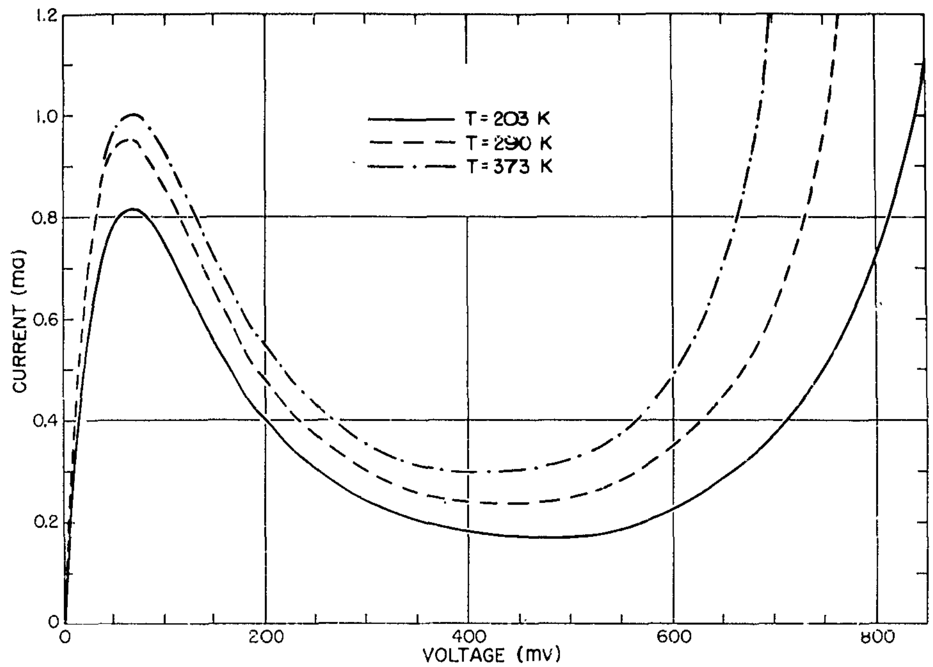

Fig. 19 D-c Characteristics of Si Tunnel Diode Type 1N2929 at 203 K, 290 K, and 373 K

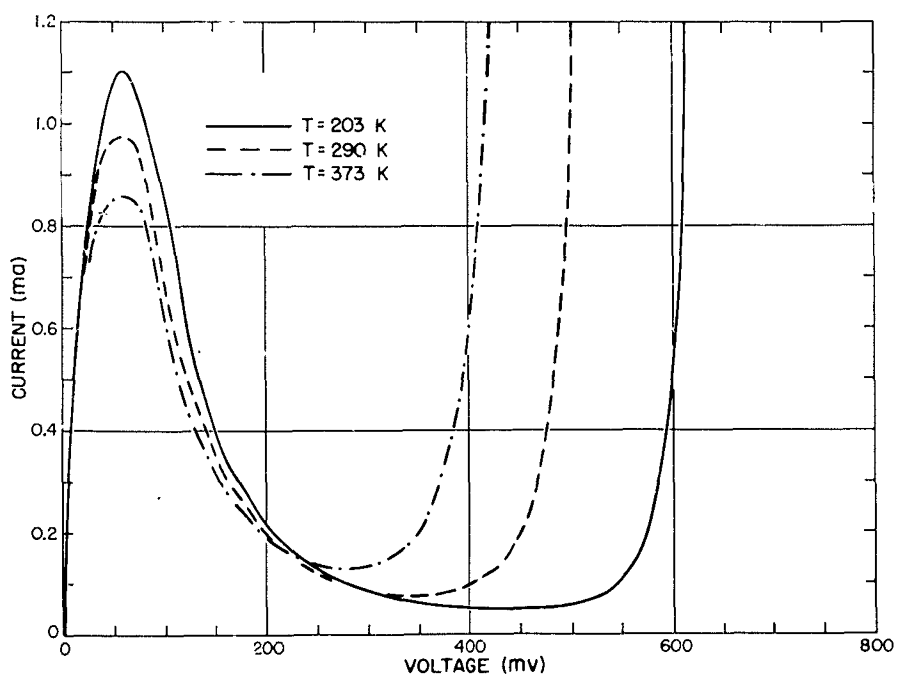

Fig. 20 D-c Characteristics of Ge Tunnel Diode Type 1N2939 at 203 K, 290 K, and 373 K

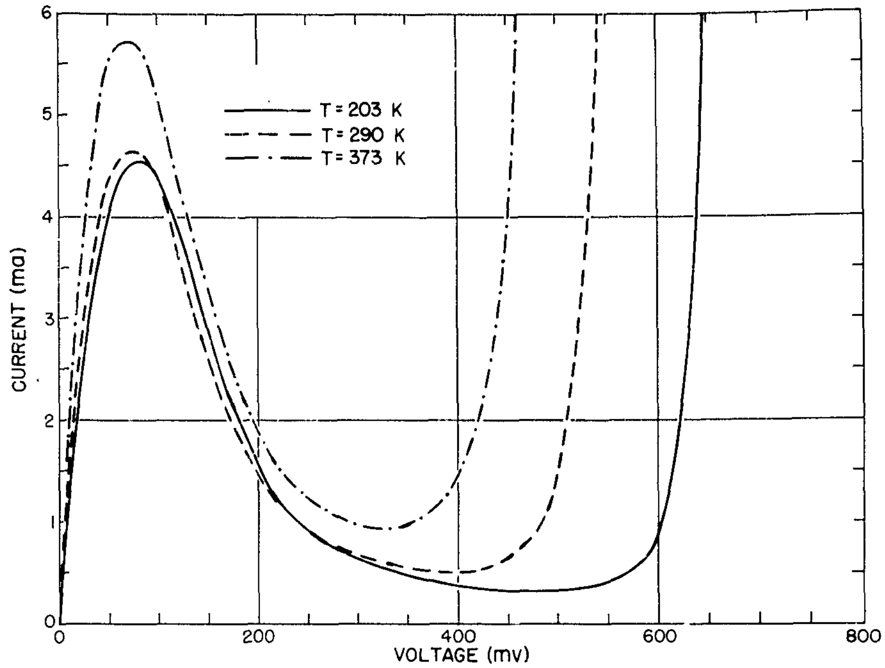

Fig. 21 D-c Characteristics of Ge Tunnel Diode Type 1N2941 at 203 K, 290 K, and 373 K

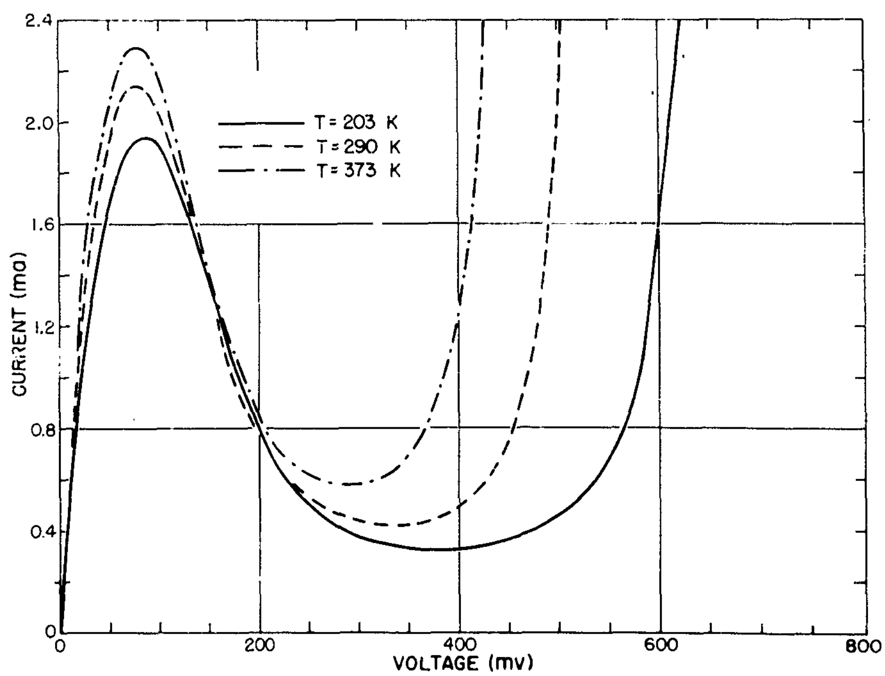

Fig. 22 D-c Characteristics of Ge Tunnel Diode Type 1N2969 (No. 1) at 203 K, 290 K, and 373 K

magnitude of the excess current is known to be relatively independent of temperature,[1] it seems necessary to assume that the noise associated with the different components of excess current are temperature dependent in different ways.

In general, the following statements can be made about excess noise in tunnel diodes :

1. 1/f noise is greatest for most tunnel diodes at the higher bias voltages.

2. At bias voltages near the valley voltage and higher, the 1/f noise may predominate at frequencies as high as 50 Mc.

Measurements by Van der Ziel[5] indicated that there are irregularities at low frequencies in the noise spectra of some tunnel diodes. No such irregularities were noted for the four samples studied.

C. SHOT NOISE IN TUNNEL DIODES

Measurements were made of the equivalent noise-current generator in parallel with four tunnel-diode samples at 30 Mc and 290 K. It was assumed that all noise measured at this frequency was frequency independent, and that the thermal noise due to the spreading resistance of the diode was negligible compared to the shot noise over the bias range of interest. The latter assumption is valid at frequencies well below the resistive cut-off frequency of the tunnel diode as long as the ratio of minimum negative resistance to spreading resistance is much greater than one. For the Type 1N2941 4.7-ma diode, this ratio is 55:1, so that the error introduced by this assumption is less than two percent. For the other diodes, the error is considerably less.

The current components I_E and I_Z were calculated for each diode by Pucel's method, and, following Tiemann,[2] it was assumed that the equivalent shot-noise current of the diode should be given by Eq. 3. Figures 23 through 26 show the measured shot-noise equivalent current for the four samples compared to the value of I_{eq} obtained from Eq. 3, the sum of I_E, I_Z, I_{ex}, and I_d.

For all diodes, the measured shot-noise equivalent current agrees very closely with Eq. 3. Such small differences as exist could be caused by the following:

1. Some $1/f$ noise may be present.
2. At higher bias voltages, the larger junction capacitance makes accurate measurement of noise difficult. The high measured values of I_{eq} at the highest bias voltages may thus be in error.
3. In the positive-resistance regions, the increased value of F_2 tends to decrease the accuracy of the measurements.

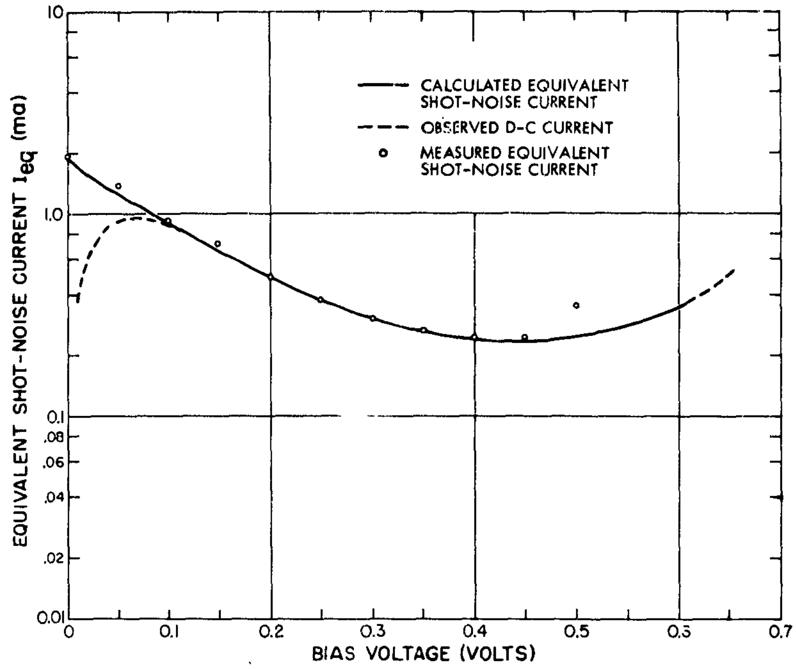

Fig. 23 Comparison of Calculated and Measured Equivalent Shot-Noise Current at 30 Mc and 290 K for Si Tunnel Diode Type 1N2929

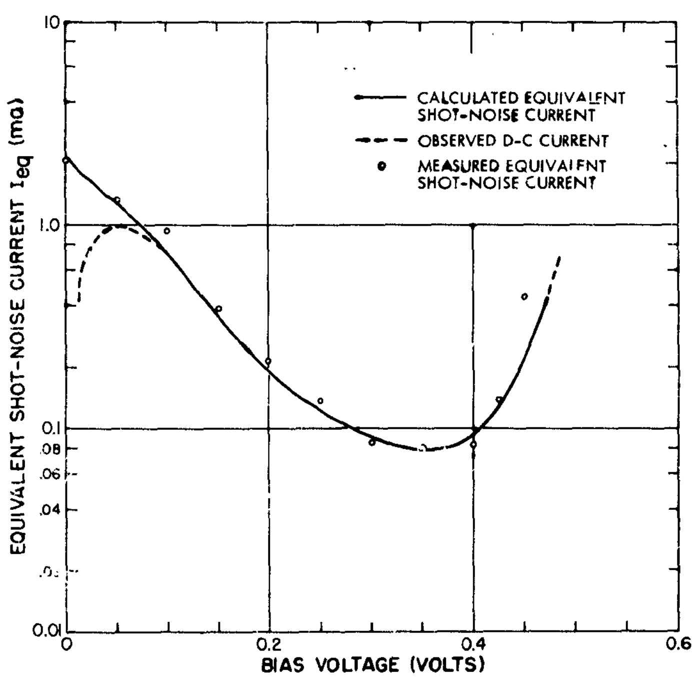

Fig. 24 Comparison of Calculated and Measured Equivalent Shot-Noise Current at 30 Mc and 290 K for Ge Tunnel Diode Type 1N2939

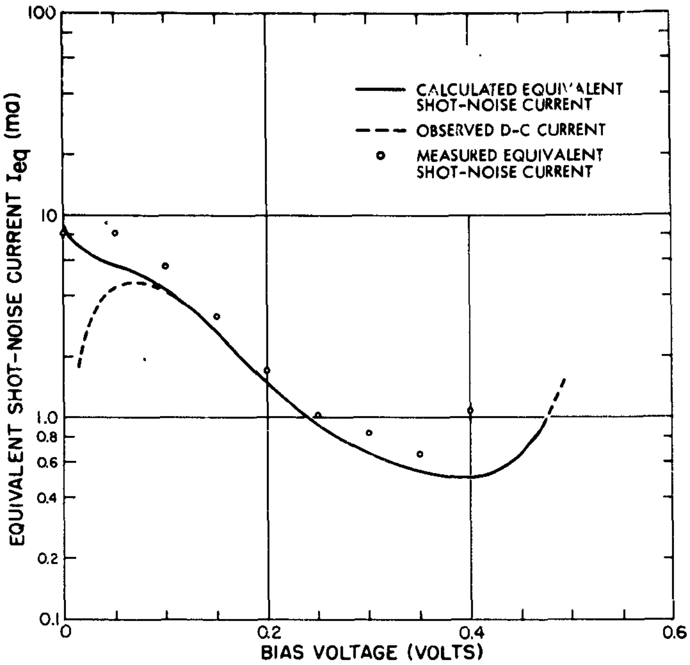

Fig. 25 Comparison of Calculated and Measured Equivalent Shot-Noise Current at 30 Mc and 290 K for Ge Tunnel Diode Type 1N2941

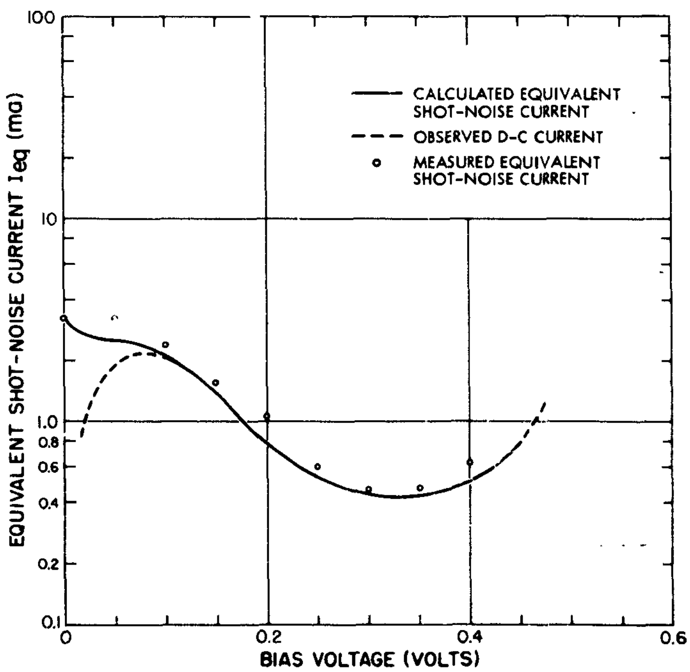

Fig. 26 Comparison of Calculated and Measured Equivalent Shot-Noise Current at 30 Mc and 290 K for Ge Tunnel Diode Type 1N2969 (No. 1)

BIBLIOGRAPHY

1. Yajima, Tatsuo; and Esaki, L., "Excess Noise in Narrow Germanium p-n Junctions," Journal of the Phys. Soc. of Japan, Vol. 13, No. 11, (November, 1958), pp. 1281-1287.

2. Tiemann, J.J., "Shot Noise in Tunnel Diode Amplifiers," Proc. I.R.E., Vol. 48, No. 8 (August, 1960), pp. 1418-1423.

3. Pucel, R.A., "The Equivalent Noise Current of Esaki Diodes," Proc. I.R.E., Vol. 49, No. 6 (June, 1961), pp. 1080-1081.

4. Davidsohn, U.S.; Hwang, Y.C.; and Ober, G.B., "Designing with Tunnel Diodes-Part I," Electronic Design, (February 3, 1960) pp. 50-55.

5. Van der Ziel, A., Noise in Semiconductors and Semiconductor Devices, University of Minnesota Progress Report, Electrical Engineering Dept., (June, 1960), pp. 83-85.

DISTRIBUTION LIST

Contract AF33(616)-5489
DSR 7848 10/60

GOVERNMENT AND MILITARY

Commander
Air Research and Development Command
Andrews Air Force Base
Washington 25, D. C.
ATTN: RDTC

Director
Air University Library
Maxwell Air Force Base
Alabama

Director of Research and Development
Headquarters, USAF
ATTN: AFDRD-SC-3
Washington 25, D. C.

Commander
Air Force Cambridge Research Center
ATTN: Electronic Research Library
230 Albany Street
Cambridge 39, Massachusetts

Commander
Rome Air Development Center
ATTN: Research Library
Griffiss Air Force Base
New York

Commander
Aeronautical Systems Division
Wright-Patterson Air Force Base
Dayton, Ohio

Attn: ASAD - Library
ASAT
ASDSEB
ASRCP
ASRNR
ASRNET-3
ASRNGE-1 (3 cc., 1 repro.)

Armed Services Technical Information Agency
ATTN: TICSC (10 cys)
Arlington Hall Station
Arlington 12, Virginia

Commanding Officer
U. S. Army Signal Research
and Development Laboratory
ATTN: SIG-EL-RDR
Fort Monmouth, New Jersey

Office of the Chief Signal Officer
Department of the Army
ATTN: Eng. and Tech. Div.
Washington 25, D. C.

Chief, Bureau of Aeronautics
Department of the Navy
ATTN: Electronics Division
Washington 25, D. C.

Chief, Bureau of Ships
Department of the Navy
ATTN: Code 816
Washington 25, D. C.

Director, Naval Research Laboratories
ATTN: Code 2021
Washington 25, D. C.

Chief, Bureau of Aeronautics
Central District
ATTN: Electronics Division
Wright-Patterson Air Force Base
Ohio

Commanding Officer
U. S. Navy Electronics Laboratory
San Diego 52, California

Commanding Officer
Office of Naval Research
346 Broadway
New York 13, New York

Assistant Secretary of Defense
Research and Development Board
Department of Defense
Washington 25, D. C.

Secretary, Committee on Electronics
Office of Asst. Secretary of Defense
Department of Defense
Washington 25, D. C.

INDUSTRIAL

Airborne Instruments Laboratory
A Division of Cutler-Hammer, Inc.
Walt Whitman Road
Melville, Long Island, New York

Batelle Memorial Institute
Solid State Devices Div.
ATTN: Mr. E. H. Layer
505 King Avenue
Columbus 1, Ohio

Bell Aircraft Corporation
P. O. Box 1
Buffalo, New York

Bell Telephone Lab.
Electronics Research Dept.
Murray Hill Lab.
Murray Hill, New Jersey

Bell Telephone Laboratories
Attn: C. W. Hoover
Whippany, New Jersey

Boeing Aircraft Corporation
Seattle, Washington

Convair Division
General Dynamics Corporation
Pamona, California

Convair Division
General Dynamics Corporation
3165 Pacific Highway
San Diego, California

Cornell Aeronautical Lab.
ATTN: Librarian
4455 Genesee Street
Buffalo 21, New York

Emerson Electric Mfg. Co.
Station 62
8100 W. Florissant Ave.
St. Louis 21, Missouri

General Electric Company
Advanced Electronics Center
Ithaca, New York

General Electric Company
Research Laboratory
1 River Road
Schenectady, New York

General Electric Company
ATTN: Director - Electronics Laboratory
Electronics Park
Syracuse, New York

General Electric Company
Light Military Electronics Equip. Dept.
French Road
Utica, New York

General Electric Company
Microwave Laboratory
601 California Avenue
Palo Alto, California

General Mills
Engineering Research and Development Dept.
2003 E. Hennepin
Minneapolis, Minnesota

General Precision Laboratories
63 Bedford Road
Pleasantville, New York

Gilfillan Brothers
1815 Venice Blvd.
Los Angeles, California

Goodyear Aircraft Corp.
Akron 12, Ohio

Goodyear Aircraft Corp.
Litchfield Park, Arizona

Haller-Raymond and Brown, Inc.
124 N. Atherton Street
State College, Pa.

Haseltine Corp.
Haseltine Electronics Division
59-25 Little Neck Parkway
Little Neck 62, New York

Hughes Aircraft Company
ATTN: Librarian
Florence and Teale Streets
Culver City, California

DISTRIBUTION LIST - Contract AF33(616)-5489

The Johns Hopkins University
Radiation Lab.
1315 St. Paul Street
Baltimore 2, Md.

Lockheed Aircraft Corp.
ATTN: Mr. F. W. Husmann
131 North Ludlow Street
Dayton 2, Ohio

W. L. Maxson Corp.
460 W. 34th Street
New York, N. Y.

McDonnell Aircraft Corp.
P.O. Box 516
St. Louis, Missouri

The Martin Electronics Company
Baltimore 3, Md.

Mitre Corporation
Library
P.O. Box 208
Bedford, Mass.

Motorola Corp
3102 North 56th Street
Phoenix, Arizona

North American Aviation
Autonetics Division
Attn: Librarian
9150 E. Imperial Hwy
Downey, California

The Ohio State University
Research Foundation
Antenna Laboratory
Attn: Dr. T. E. Tice
1314 Kinnear Road
Columbus 8, Ohio

Philco Corp.
Attn: Librarian
4700 Wissahickon Ave.
Philadelphia 44, Pa.

Radio Corporation of America
Bldg. 108-1
Moorestown, N. J.

Radio Corporation of America
RCA Lab.
Princeton, New Jersey

Radio Corporation of America
Missile Electronics and Controls Dept.
Woburn Post Office
Woburn, Mass.

Ramo-Wooldridge
A Division of Thompson
Ramo Wooldridge Inc.
8433 Fallbrook Ave.
Canoga Park, California

Raytheon Manufacturing Co.
Missile and Radar Div.
Bedford, Mass

Republic Aviation
Attn: Eng. Library
Farmingdale, Long Island
New York

Republic Aviation Corp.
Guided Missiles Div.
233 Jericho Turnpike
Mineola, New York

Sanders Associates, Inc.
Attn: Document Librarian
95 Canal Street
Nashua, New Hampshire

Sandia Corporation
Sandia Base
Albuquerque, New Mexico

Space Electronics Corp.
930 Air Way
Glendale 1, California

Sperry Gyroscope Co.
Attn: Librarian
Great Neck, Long Island
New York

Sperry Microwave Electronics Co.
Attn: Mr. R. E. Lazarchik
Clearwater, Florida

Stanford Research Institute
Division of Engineering Research
Stanford, California

Stavid Engineering, Inc.
U. S. Highway 22
Plainfield, New Jersey

Sylvania Electric Products, Inc.
500 Evelyn Avenue
Mountain View, California

Sylvania Electric Products, Inc.
Waltham Lab. Library
100 First Avenue
Waltham, Mass.

Technical Research Group, Inc.
2 Aerial Way
Syosset, N. Y.

Texas Instruments, Inc.
ATTN: Apparatus Div. Library
6000 Lemon Avenue
Dallas 9, Texas

University of Illinois
Control Systems Lab.
Urbana, Illinois

University of Michigan
Engineering Research Institute
Attn: Director Electronic Defense Group
Ann Arbor, Michigan

University of Michigan
Willow Run Laboratories
Ypsilanti, Michigan

Westinghouse Electric Corp.
Air Arm Division
Attn: Librarian
Friendship International Airport
Baltimore 3, Md.

Wiley Electronics Co.
2045 West Cheryl Drive
Phoenix, Arizona

North American Aviation
Missile Division
12214 Lakewood Blvd.
Downey, California

Giannini Controls Corp.
Library
1600 So. Mountain Ave.
Duarte, California

GOVERNMENT AND MILITARY
(continued)

Space Technology Lab Inc.
P.O. Box 95001
Los Angeles 45, Calif.
Attn: Tech. Information Center
Document Procurement

*Unclassified Reports

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

UNCLASSIFIED

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

UNCLASSIFIED

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

UNCLASSIFIED

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

UNCLASSIFIED

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

UNCLASSIFIED

AD
Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
AN EXPERIMENTAL INVESTIGATION OF NOISE IN TUNNEL DIODES by Carl N. Berglund. July 1961. 32p. incl. illus. (Contract AF-33(616)-5489, Task 50688, MIT Project DSR 7848) Report ESL-R-115
Unclassified report

Noise measurements were made on one silicon and three germanium commercially available tunnel diodes over a bias range from zero voltage to a voltage slightly beyond the valley point, and at three temperatures--203 K, 290 K, and 373 K. The study was divided into two parts, one concerned with frequency-dependent noise and the other with frequency-independent noise.

Frequency-dependent noise was measured in the range 1 kc to 500 kc, and was found to increase with increasing bias voltage for each sample. The observed noise at each bias point varied nearly inversely as the frequency to some power x, where x ranged from 0.46 to 1.2. This component of noise appears to be caused by

(over)

UNCLASSIFIED

UNCLASSIFIED

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

two or more separate components of the "excess current" present, as well as the normal diode component of current. For some tunnel diodes at the higher bias voltages, frequency-dependent noise may be greater than the normal shot noise at frequencies as high as 50 Mc.

Frequency-independent noise was measured at 30 Mc at room temperature. It was found that the equivalent shot-noise current of a tunnel diode at voltages above the peak-point voltage is given very closely by the observed direct current. From zero voltage to the peak-point voltage, the equivalent shot-noise current of a tunnel diode is approximated by the sum of the magnitudes of the Esaki and Zener currents.

LIST OF REPORTS PUBLISHED ON THIS CONTRACT

REPORT NO.	ASTIA NO.	CLASSIFICATION	TITLE	AUTHOR(S)	DATE
7848-R-1	AD 210 247	Unclassified	A Transistor-Magnetic Pulse Generator for Radar-Modulator Applications	Krinitz, A.	/58
7848-R-3	AD 306 104	Confidential	Radar System and Component Research 1958 Annual Report	Staff	[illegible]
7848-R-3a		Unclassified	Unclassified Radar System and Component Research	Staff	[illegible]
7848-R-4	AD 210 245	Unclassified	Video-Frequency Noise Measurements on Microwave Crystal Mixers	Newberg, I. L.	8/59
7848-7849-R-4	AD 210 245	Unclassified	Electrical Properties of Thin Film of Cadmium Sulfide	MacArthur	[illegible]/58
7848-7849-R-7	AD 217 730	Unclassified	A Theory of Multiple-Scan Surveillance Systems	Kennedy, R. S.	5/59
7848-7849-R-12	AD 247 436	Unclassified	Investigation of a Thin-Film Thermal Transducer	Gottling, J. G.	[illegible]/60
ESL-AR-104(1)		Unclassified	Investigation of New Radar Components and Techniques--1960 Annual Report (Vol. I)	Staff	9/59-8/60
ESL-AR-104(2)		Confidential	(Unclassified Title) Investigation of New Radar Components and Techniques--1960 Annual Report (Vol. II)	Staff	9/59-8/60
ESL-R-115		Unclassified	An Experimental Investigation of Noise in Tunnel Diodes	Berglund, C. N.	7/[illegible]

TECHNICAL MEMORANDA

REPORT NO.	ASTIA NO.	CLASSIFICATION	TITLE	AUTHOR(S)	DATE
7848-7849-TM-1	AD 210 244	Unclassified	Theory of a Fast-Response Thin Film Thermal Transducer	Gottling, J. G.	7/58
7848-TM-2	AD 213 521	Unclassified	High-Power Pulse Generation Using Semiconductors and Magnetic Cores	Lassiter, I. M.	[illegible]/59
7848-TM-3	AD 218 233	Unclassified	Some Data on Video-Frequency Noise Temperatures of Balanced X-Band Crystal Mixers	Newberg, I. I.	[illegible]
7848-7849-TM-4	AD 228 065	Unclassified	Optical Data-Processing With Thin Magnetic Film	Kleinrock, [illegible]	[illegible]
7848-TM-5	AS 220 717	Unclassified	A Regulated Power Supply for Airborne Radar	Kapp, E.	[illegible]
~~7848-TM-6~~	~~AD 231 938~~	Unclassified	Supplement to "Video-Frequency Noise Measurements on Microwave Crystal Mixers"--Data for Germanium Crystals	Newberg, I. L.	11/[illegible]
7848-7849-TM-7	AD 234 506	Unclassified	Thin Film Conductivity Modulation by the Electrolysis of Glass Substrate	Advani, G.	2/[illegible]
7848-7849-TM-8	AD 242 253	Unclassified	A Study of the Enhancement of the Kerr Rotation	Cole, F. B.	4/[illegible]
7848-7849-TM-9	AD 247 433	Unclassified	An Investigation of the Vacuum Evaporation Techniques of Electroluminescent Phosphors	Tarjan, P. P.	10/[illegible]
ESL-TM-100		Unclassified	Tunnel Diode Circuits for Switching Thin Film Memories	Davis, P. C.	[illegible]
ESL-TM-105	AD 259 333	Unclassified	A Method for Fabricating Thin Ferroelectric Films of Barium Titanate	Green, J. P.	[illegible]
ESL-TM-117		Unclassified	Measurements of Shot No[illegible] in Tunnel Diodes at Low Forw[illegible] Voltages	Berglund, C. N	[illegible]